Journal of Civil Engineering and Applications

E-ISSN: 2707-8396
P-ISSN: 2707-8388
Impact Factor (RJIF): 5.15
www.civilengineeringjournals.com/jcea
JCEA 2026; 7(2): 01-12
Received: 10-04-2026
Accepted: 15-05-2026

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Floodplain impacts on road infrastructure in the Niger delta: Implications for pavement design, construction and maintenance

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DOI: https://www.doi.org/10.22271/27078388.2026.v7.i2a.81

Abstract
Road infrastructure in the Niger Delta is increasingly threatened by recurrent flooding, weak floodplain soils, and inadequate drainage systems, resulting in premature pavement deterioration and escalating maintenance costs. This study evaluated the impacts of floodplain conditions on road infrastructure development in the Niger Delta through an integrated assessment of geotechnical characteristics, environmental conditions, soil stabilization, asphalt mixture performance, pavement structural design, and life-cycle cost. Representative soil samples were collected from six flood-prone locations across the region and subjected to laboratory testing, including particle size distribution, Atterberg limits, compaction, California Bearing Ratio (CBR), and Marshall Mix Design. Pavement structural analysis and life-cycle cost evaluation were subsequently performed to compare conventional and improved pavement systems. The investigated soils were predominantly fine-grained, with 49.1-57.3% passing the 0.075 mm sieve. The soils exhibited liquid limit values ranging from 35.6% to 53.7%, plasticity indices of 14.7-25.9%, and CBR values between 18% and 30%, confirming moderate to highly plastic subgrade conditions with poor engineering suitability under saturated conditions. Environmental assessment further revealed annual rainfall ranging from 2,085 mm to 3,735 mm, frequent flooding, shallow groundwater conditions, and inadequate drainage, all of which contributed to accelerated pavement deterioration. Cement stabilization significantly improved subgrade performance by increasing the CBR from 22.0% to 48.4%, representing an improvement exceeding 120%, while reducing the plasticity index from 25.9% to 10.4%. The modified asphalt mixture also demonstrated superior engineering performance, with Marshall Stability increasing from 12 kN to 15 kN, accompanied by improved volumetric properties that enhanced resistance to moisture-induced damage. Structural pavement analysis showed that improving subgrade conditions reduced the required pavement thickness from 580 mm for the conventional pavement to 450 mm for the stabilized pavement. The life-cycle cost analysis indicated that although the improved pavement required a higher initial investment, it achieved the lowest long-term cost of approximately ₦23,000/m², compared with ₦30,000/m² for the conventional pavement, and recorded the highest cost-effectiveness index of 0.00283. The findings demonstrate that integrating subgrade stabilization, modified asphalt technology, effective drainage, and climate-responsive pavement design substantially improves the durability, resilience, and economic sustainability of road infrastructure in floodplain environments, providing practical engineering solutions for the Niger Delta and other flood-prone regions.

Keywords: Floodplain, road infrastructure, pavement engineering, soil stabilization, modified asphalt mixtures, california bearing ratio (CBR), marshall stability, pavement design, life-cycle cost analysis

Introduction
Transportation infrastructure plays a fundamental role in promoting economic development, regional integration, and social connectivity by facilitating the efficient movement of people, goods, and services. Among the various transportation modes, road networks constitute the most widely utilized infrastructure system because of their accessibility and direct linkage to industrial, commercial, and residential areas. Consequently, maintaining the structural integrity and serviceability of road infrastructure has become a major priority for governments and transportation agencies worldwide. However, the increasing frequency and intensity of flood events, driven by climate variability, rapid urbanization, and changes in land use, have significantly increased the vulnerability of road networks to structural deterioration, service disruptions, and escalating maintenance costs (Mushtaq *et al.*, 2024; Lang *et al.*, 2024; Muhammad *et al.*, 2024; World Bank, 2024) [16, 11, 15, 29].

Recent investigations indicate that flood-induced pavement failures account for a substantial proportion of transportation infrastructure losses in many developing countries, highlighting the urgent need for resilient engineering strategies capable of sustaining road performance under extreme hydrological conditions (Chen & Wang, 2024; Peng *et al.*, 2025; Rajput *et al.*, 2022) [8, 21, 22].

Flooding affects road infrastructure through a combination of hydraulic, geotechnical, and environmental processes that collectively reduce pavement durability and structural capacity. Prolonged inundation weakens pavement layers by increasing moisture infiltration into asphalt mixtures, base courses, subbase materials, and supporting subgrade soils, thereby reducing bearing capacity and accelerating deterioration mechanisms such as rutting, stripping, pothole formation, fatigue cracking, and differential settlement (Mousa *et al.*, 2023; Yadav *et al.*, 2024; Chen & Wang, 2024). These effects are often exacerbated by inadequate drainage systems, undersized hydraulic structures, sediment accumulation, and blocked drainage channels that prevent the rapid removal of stormwater from pavement surfaces (Adaba & Agunwamba, 2015; Mokuolu *et al.*, 2020; Adeogun *et al.*, 2024; Bayou *et al.*, 2025). Consequently, effective drainage design has become an indispensable component of modern highway engineering because it directly influences pavement performance, infrastructure resilience, maintenance requirements, and long-term economic sustainability [14, 30, 1, 13, 2, 5].

The hydraulic capacity of road drainage systems is commonly estimated using the Rational Method, which provides the peak runoff expected from a drainage catchment during a design storm. The relationship is expressed as Equation (1):

$$Q = C\,I\,A \tag{1}$$

Where Q is the peak runoff, C is the runoff coefficient, I is the rainfall intensity, and A is the drainage catchment area. Although relatively simple, this equation remains widely adopted in highway drainage design because it provides a practical basis for sizing drainage structures and evaluating stormwater management systems (Texas Department of Transportation, 2024; Ahmad *et al.*, 2024; Panguriseng *et al.*, 2024). However, recent studies have emphasized that conventional drainage design approaches based solely on historical rainfall records may underestimate runoff under changing climatic conditions, thereby increasing the susceptibility of road infrastructure to flood-induced failures (Fereshtehpour *et al.*, 2025; Khatooni *et al.*, 2025; Li *et al.*, 2025) [26, 3,10, 12].

The Niger Delta is one of the largest deltaic systems in Africa and is characterized by extensive floodplains, wetlands, mangrove swamps, tidal creeks, and low-lying coastal terrains. The region experiences prolonged seasonal rainfall, high groundwater levels, poor natural drainage, and periodic overbank flooding resulting from the Niger River and its numerous distributaries (Food and Agriculture Organization [FAO], 1973; Britannica, 2026; Bridge, 2003) [9]. These unique geomorphological and hydrological conditions support important ecological functions and economic activities, including agriculture, fisheries, petroleum exploration, and inland transportation. However, they also present significant engineering challenges for the planning, construction, and maintenance of transportation infrastructure. Previous studies have shown that road pavements constructed within floodplain environments are continually exposed to saturated subgrade conditions, fluctuating groundwater tables, and repeated hydraulic loading, all of which accelerate structural deterioration and shorten pavement service life (Broll & El Hourani, 2021; Ogunkoya & Olayiwola, 2022; Okeibunor Nwambuonwo *et al.*, 2024; Ugwu *et al.*, 2025) [6, 17, 18, 19, 28].

From an engineering standpoint, the performance of road infrastructure in floodplain environments is governed by the combined interaction of hydrological conditions, pavement materials, drainage efficiency, and subgrade characteristics. Excessive moisture infiltration reduces the strength of fine-grained soils, decreases California Bearing Ratio (CBR) values, increases pavement deflections, and accelerates distress mechanisms such as rutting, fatigue cracking, edge failure, and pothole development (Mousa *et al.*, 2023; Chen & Wang, 2024; Yadav *et al.*, 2024; Peng *et al.*, 2025) [14, 30]. Simultaneously, inadequate drainage systems prolong the retention of stormwater within pavement layers, reducing the effectiveness of conventional pavement designs and increasing maintenance frequency. Consequently, sustainable highway development within floodplain regions requires an integrated engineering approach that combines hydrological assessment, geotechnical investigation, effective drainage design, durable pavement materials, and long-term maintenance planning rather than relying solely on conventional structural design procedures (Awwad, 2021; Engineering Science Journal, 2023; Roads for Water, 2024; Bayou *et al.*, 2025; Siregar *et al.*, 2025) [4, 23, 24].

Recent research has demonstrated considerable progress in improving the resilience of road infrastructure through enhanced drainage design, advanced hydrological modelling, improved pavement materials, and climate-responsive engineering practices. Hydraulic assessment studies have shown that increasing the capacity of culverts, storm drains, and open channels significantly reduces flood occurrence and improves stormwater conveyance in urban road networks (Adeogun *et al.*, 2024; Egop & Umeadi, 2024; Sobowale *et al.*, 2024). Similarly, the integration of Geographic Information Systems (GIS), the Storm Water Management Model (SWMM), and Hydraulic Engineering Center River Analysis System (HEC-RAS) has substantially improved flood prediction, drainage analysis, and infrastructure planning in flood-prone environments (Ahmad *et al.*, 2024; Khatooni *et al.*, 2025; Li *et al.*, 2025; Yustiana *et al.*, 2024) [2, 3, 10, 12]. Parallel developments in pavement engineering have demonstrated that modified asphalt mixtures, improved drainage coefficients, and subgrade stabilization techniques enhance pavement durability by reducing moisture susceptibility and improving structural capacity under saturated conditions (Chen & Wang, 2024; Mousa *et al.*, 2023; Yadav *et al.*, 2024; Peng *et al.*, 2025) [24, 20, 31].

Despite these advances, the existing body of knowledge remains largely fragmented. Most previous investigations have examined drainage performance, flood modelling, pavement material behaviour, subgrade improvement, or infrastructure resilience as independent engineering problems. Comparatively few studies have integrated hydrological assessment, geotechnical characterization, pavement structural evaluation, drainage performance, and economic analysis within a single engineering framework capable of addressing the complex interactions governing road infrastructure performance in floodplain environments

(Mushtaq *et al.*, 2024; Lang *et al.*, 2024; Siregar *et al.*, 2025). Furthermore, although several international studies have focused on flood-resilient transportation systems, relatively limited research has comprehensively evaluated these interacting factors under the unique hydrogeological, climatic, and geotechnical conditions of the Niger Delta. The region's combination of weak alluvial soils, prolonged seasonal flooding, high groundwater levels, and aging drainage infrastructure presents engineering challenges that differ considerably from those reported in many temperate environments (Broll & El Hourani, 2021; Ogunkoya & Olayiwola, 2022; Okeibunor Nwambuonwo *et al.*, 2024; Ugwu *et al.*, 2025) [7, 18, 19, 28].

Addressing these challenges requires an integrated engineering approach that extends beyond conventional pavement design by incorporating floodplain characteristics, hydrological processes, drainage efficiency, pavement material performance, subgrade improvement, and long-term economic sustainability into infrastructure decision-making. Such an approach not only improves the structural reliability of road networks but also enhances climate resilience, minimizes maintenance interventions, and reduces life-cycle costs. Accordingly, this study evaluates the impacts of floodplain conditions on road infrastructure development in the Niger Delta by integrating geotechnical investigation, hydrological assessment, drainage evaluation, pavement engineering, soil stabilization, modified asphalt technology, and life-cycle cost analysis. The findings provide practical engineering strategies for improving the design, construction, and maintenance of roads in flood-prone environments while contributing to the growing body of knowledge on resilient transportation infrastructure under changing climatic conditions.

2. Materials and Methods

2.1 Study Area

The study was conducted within selected floodplain environments across the Niger Delta region of Nigeria, with representative sampling locations in Rivers, Bayelsa, Delta, Akwa Ibom, Cross River, and Edo States. These locations were selected because of their recurrent flooding, weak alluvial subgrade soils, high groundwater tables, and frequent road infrastructure failures, making them representative of the engineering challenges associated with road development in flood-prone environments. The study area lies approximately between latitudes 4.15°N and 6.50°N and longitudes 5.00°E and 7.50°E. The terrain is generally flat and low-lying, with elevations only a few metres above mean sea level, resulting in poor natural drainage and prolonged surface water retention during intense rainfall events. Annual rainfall ranges between 1,500 and 2,500 mm, with peak precipitation occurring between July and September, while flooding is influenced by local rainfall, upstream discharge from the Niger-Benue river system, and tidal interactions from the Atlantic Ocean. These hydrological conditions create prolonged periods of subgrade saturation that significantly reduce pavement performance. The predominant soils are alluvial deposits consisting of varying proportions of clay, silt, and sand, characterized by high moisture content, moderate to high plasticity, low shear strength, and poor bearing capacity under saturated conditions. These characteristics make the region suitable for evaluating the influence of floodplain conditions on pavement behaviour and assessing engineering strategies for improving road infrastructure resilience.

2.2 Soil Sampling and Pavement Condition Assessment

Representative disturbed soil samples were collected from six flood-prone locations across the study area at a uniform depth of 1.0 m below the ground surface, corresponding to the typical subgrade level of highway pavement structures. Sampling locations were selected based on flood susceptibility, accessibility, and the presence of existing road infrastructure, while their geographical coordinates were recorded using a handheld Global Positioning System (GPS) receiver to ensure reproducibility. Following removal of the organic surface layer, soil samples were obtained using hand augers, sealed in airtight containers to preserve their natural moisture condition, labelled appropriately, and transported to the laboratory for analysis.

During field sampling, observations were made regarding soil texture, colour, moisture condition, groundwater occurrence, drainage characteristics, and evidence of previous flooding. In addition, pavement condition assessments were conducted through visual inspections of representative road sections to identify common forms of distress associated with floodplain environments, including rutting, pothole formation, longitudinal and transverse cracking, edge failure, and surface deformation. These observations provided qualitative evidence linking pavement deterioration with subgrade weakening and poor drainage conditions, thereby complementing the laboratory investigations.

2.3 Laboratory Investigation

Laboratory testing commenced with sample preparation, during which soil specimens were air-dried, gently pulverized, and sieved to obtain uniform test materials while preserving their natural particle characteristics. Moisture content was adjusted where necessary, and samples requiring stabilization were thoroughly blended with predetermined quantities of cement before compaction and curing. Asphalt specimens were prepared using heated aggregates and bitumen in accordance with the Marshall Mix Design procedure.

Geotechnical characterization included particle size distribution, Atterberg limits, Standard Proctor compaction, and California Bearing Ratio (CBR) tests. Grain size analysis was performed to classify the soils and evaluate their drainage characteristics, while Atterberg limits were determined to assess soil consistency and plasticity. Compaction tests established the optimum moisture content (OMC) and maximum dry density (MDD), whereas CBR tests were conducted under both unsoaked and soaked conditions to simulate field performance before and after prolonged flooding. The soaked CBR values were subsequently adopted for pavement design because they represent the most critical subgrade condition in floodplain environments. The moisture content of each specimen was determined using Equation (2):

$$w = (W\_w / W\_s) \times 100 \quad (2)$$

Where w is the moisture content (%), Ww is the mass of water, and Ws is the mass of dry soil.

The California Bearing Ratio was determined as Equation(3):

$$CBR = (Test\ Load\ /\ Standard\ Load) \times 100 \quad (3)$$

Where the test load represents the measured penetration resistance of the specimen and the standard load corresponds to the reference penetration load.

2.4 Soil Stabilization and Asphalt Mix Design

To improve the engineering performance of the floodplain soils, Ordinary Portland Cement (OPC) was used as the stabilizing agent. The selected stabilizer was thoroughly blended with the natural soils at predetermined proportions based on the experimental programme before the addition of water. The mixtures were mechanically homogenized to ensure uniform distribution of cement particles and subsequently compacted at their respective optimum moisture contents. The stabilized specimens were cured under controlled laboratory conditions before undergoing compaction and California Bearing Ratio (CBR) testing. Comparative analyses were performed between untreated and stabilized soils to quantify improvements in bearing capacity, plasticity characteristics, moisture resistance, and overall subgrade performance. The effectiveness of stabilization was assessed based on changes in maximum dry density (MDD), optimum moisture content (OMC), Atterberg limits, and soaked CBR values, which served as the principal design parameters for pavement structural analysis.

The suitability of asphalt mixtures for flood-prone environments was evaluated using the Marshall Mix Design method. Coarse aggregate, fine aggregate, mineral filler, and penetration-grade bitumen were proportioned in accordance with standard asphalt mix design procedures. Aggregates were oven-dried, graded, and heated together with the bitumen before mixing at the prescribed temperatures to ensure complete coating of aggregate particles. The prepared mixtures were compacted using the standard Marshall compaction hammer with the specified number of blows applied to each face of the specimen. After cooling, the specimens were conditioned in a thermostatically controlled water bath prior to testing for Marshall stability and flow.

Marshall testing was undertaken to determine the optimum bitumen content and evaluate the mechanical performance of both conventional and modified asphalt mixtures. The principal parameters determined included Marshall Stability, Flow, Bulk Density, Air Voids (AV), Voids in Mineral Aggregate (VMA), and Voids Filled with Bitumen (VFB). These parameters were subsequently compared with established pavement design specifications to determine the suitability of each mixture for floodplain road construction. The optimum binder content was selected from the combined analysis of density, stability, flow, and volumetric properties to achieve an asphalt mixture capable of resisting moisture-induced deterioration while maintaining adequate structural performance under traffic loading.

2.5 Pavement Structural Design and Life-Cycle Cost Analysis: The engineering properties obtained from the laboratory investigations formed the basis for the structural design of flexible pavement alternatives. Pavement thicknesses were determined using the soaked CBR values obtained from untreated and stabilized subgrade soils to represent the critical field conditions associated with prolonged flooding. Separate pavement structures were developed for conventional and improved pavement systems, enabling direct comparison of layer thicknesses, structural capacity, and anticipated field performance under identical traffic loading conditions. The design process considered the engineering characteristics of the subgrade together with the strength contribution of the pavement layers to ensure that the resulting structures could adequately distribute traffic loads while minimizing excessive deformation.

The structural adequacy of the pavement was evaluated using the Structural Number (SN), expressed as Equation (4):

$$SN = a_1D_1 + a_2D_2m_2 + a_3D_3m_3 \quad (4)$$

Where *SN* = Structural Number; *a* = structural layer coefficient; v*D* = layer thickness (mm); and *m* = drainage coefficient for each pavement layer.

The incorporation of drainage coefficients enabled the structural design to account for the influence of moisture on pavement performance, recognizing that inadequate drainage significantly reduces the effective structural capacity of flexible pavements in flood-prone environments.

A comparative life-cycle cost analysis (LCCA) was subsequently undertaken to evaluate the long-term economic performance of the alternative pavement systems. The analysis incorporated initial construction costs, routine maintenance, periodic rehabilitation, and anticipated service life over the design period. Cost data were analyzed to determine the most economically sustainable pavement option capable of providing improved structural performance under recurrent flooding conditions. By considering both engineering performance and economic efficiency, the study established a practical basis for selecting pavement alternatives suitable for floodplain environments where maintenance costs and infrastructure downtime are major concerns.

2.7 Data Analysis

The experimental data obtained from the field investigations, laboratory tests, pavement design, and life-cycle cost analysis were organized and analyzed using descriptive and comparative engineering approaches. Geotechnical parameters including particle size distribution, Atterberg limits, moisture content, maximum dry density, optimum moisture content, and California Bearing Ratio were statistically summarized and compared for untreated and stabilized soil specimens to evaluate the influence of stabilization on subgrade behaviour. Similarly, Marshall mix properties comprising stability, flow, bulk density, air voids, voids in mineral aggregate, and voids filled with bitumen were analyzed to determine the optimum asphalt mixture for floodplain applications.

Comparative assessments were further undertaken to evaluate differences between conventional and modified pavement systems in terms of structural thickness, engineering performance, and life-cycle cost. The analytical results were presented using tables and figures to facilitate interpretation, while engineering performance was assessed with reference to established pavement design standards and relevant highway engineering specifications. The integrated analysis provided a comprehensive evaluation of the effects of floodplain conditions on road infrastructure development and enabled the identification of engineering strategies capable of enhancing pavement resilience, durability, and long-term economic sustainability under recurrent flooding conditions.

3. Results and Discussion

The engineering performance of road infrastructure constructed on floodplain soils is strongly influenced by the physical and geotechnical properties of the underlying subgrade materials. To evaluate the suitability of the selected floodplain soils for pavement construction, particle size distribution, consistency characteristics, soil classification, and representative geotechnical properties were determined. The summarized results are presented in Tables 1-3, while the corresponding particle size distribution and plasticity characteristics are illustrated in Figures 1 and 2.

Table 1: Combined Gradation

Particle Size (mm)	Rumuokoro	Yenagoa	Warri	Uyo	Calabar	Benin
4.75	98.9	99.2	98.9	98.8	98.6	98.1
2.36	96.8	97.8	97	96.7	96.2	95.2
2	95.4	96.8	95.8	95.4	94.8	93.5
1.4	92	94.4	92.9	92.3	91.4	89.6
1.18	90.1	93	91.3	90.5	89.5	87.5
1	83.3	88.1	85.5	84.2	82.7	79.7
0.5	70	73.8	73.2	72.9	72.4	70.4
0.25	57.7	60	61.9	63.1	63.1	62.6
0.15	49.8	51.1	54.5	56.7	57.2	57.7
0.075	49.1	50	53.9	56.2	56.7	57.3
0.0483	38.7	42.7	38	38.4	39.2	35.2
0.0217	37.4	41.4	36.7	37.2	38	34
0.0126	35.7	39.7	35.1	35.4	36.2	32.2
0.009	34.4	38.4	33.9	34.2	35	31
0.0064	33.7	37.7	33.2	33.5	34.2	30.2
0.0045	33.1	37	32.6	32.8	33.6	29.6
0.0032	32	35.8	31.5	31.7	32.4	28.5
0.0026	31.6	35.4	31.1	31.3	32	28.1
0.0023	31.3	35.1	30.8	31	31.7	27.8
0.0013	31.1	34.8	30.5	30.7	31.4	27.5

Table 2: Soil Classification

Location	LL (%)	PL (%)	PI (%)	% Passing (75 µm)	USCS Class	AASHTO Class	Soil Description
Port Harcourt	52.7	26.8	25.9	49.1	CL-CH	A-7-6	Clayey soil (high plasticity)
Yenagoa	53.7	29.8	23.9	50	CH	A-7-6	Highly plastic clay
Warri	51	27.3	23.7	53.9	CH	A-7-6	Clayey soil
Uyo	46.8	26.3	20.5	56.2	CL	A-7-6	Medium plastic clay
Calabar	41.8	24.7	17.1	56.7	CL-ML	A-7-5	Silty clay
Benin City	35.6	20.9	14.7	57.3	ML	A-6	Silty soil / sandy silt

Table 3: Location-Based Geotechnical and Pavement Characteristics

Location	State	Soil Classification	Liquid Limit (%)	Plasticity Index (%)	CBR (%)	Flood Severity	Pavement Condition
Port Harcourt	Rivers	Clayey Sand (SC)	48	22	20	High	Poor
Yenagoa	Bayelsa	Silty Clay (CL)	55	28	18	Very High	Very Poor
Warri	Delta	Clayey Silt (ML/CL)	50	24	23	High	Poor
Uyo	Akwa Ibom	Sandy Clay (SC)	45	20	25	Moderate	Fair
Calabar	Cross River	Silty Sand (SM)	42	18	26	Moderate-High	Fair
Benin City	Edo	Well-graded Sand (SW)	35	12	30	Low-Moderate	Good

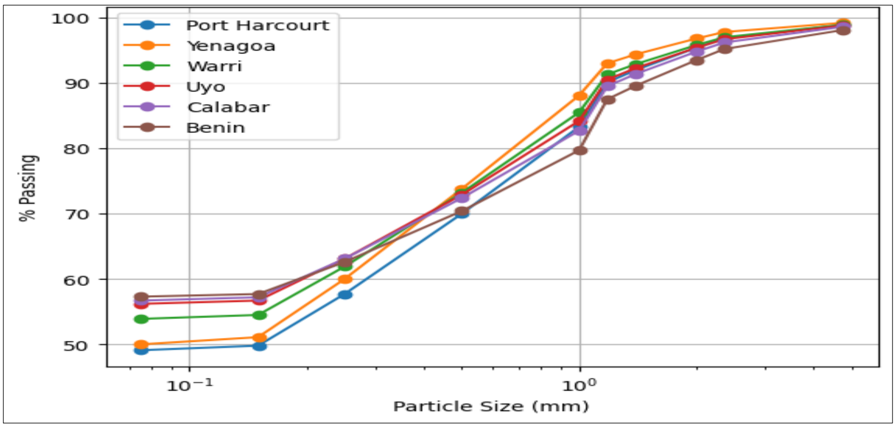

Fig 1: Grain Size Distribution

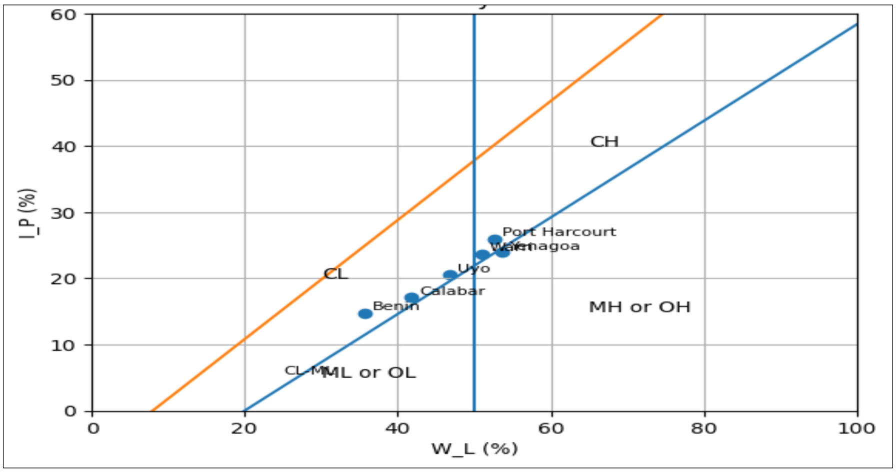

Fig 2: Plasticity chart

The engineering classification further revealed liquid limit values between 35.6% and 53.7% and plasticity indices ranging from 14.7% to 25.9%, classifying most of the soils as CL, CH, or CL-CH under the Unified Soil Classification System and A-7-5/A-7-6 under the AASHTO system. These classifications indicate moderate to highly plastic soils with poor subgrade characteristics, particularly under saturated conditions. Similar findings have been reported for floodplain soils where high clay content and moisture susceptibility significantly reduce pavement performance (Chen & Wang, 2024; Bayou *et al.*, 2025) [8].

The plasticity chart (Figure 2) shows that most samples plot within the medium- to high-plasticity region, suggesting a high potential for volume change and reduced bearing capacity during prolonged wet conditions. This observation is consistent with the field assessment presented in Table 3, where locations exhibiting higher plasticity generally recorded poorer pavement conditions and lower California Bearing Ratio (CBR) values. For example, Yenagoa recorded the highest liquid limit and one of the lowest CBR values, corresponding to severe pavement deterioration, whereas Benin City exhibited comparatively lower plasticity and better pavement performance.

Overall, the results demonstrate a strong relationship between soil plasticity, bearing capacity, and pavement condition within the study area. The predominance of cohesive, moisture-sensitive soils explains the frequent pavement failures observed across flood-prone sections of the Niger Delta. These findings agree with recent studies which concluded that weak alluvial subgrades significantly increase the vulnerability of road infrastructure to flood-induced deterioration and emphasize the need for appropriate soil stabilization and efficient drainage systems to improve long-term pavement performance (Mushtaq *et al.*, 2024; Peng *et al.*, 2025; Siregar *et al.*, 2025) [21].

The performance of existing road infrastructure within the selected floodplain environments was evaluated using environmental conditions, subgrade strength, and pavement performance indicators. The summarized results are presented in Tables 4-6, while the relationship between subgrade strength and pavement performance is illustrated in Figure 3.

Table 4: Environmental Summary

Location	**Annual Rainfall (mm)**	**Rainfall Class**	**Flood Frequency (times/year)**	**Flood Duration (days)**	**Flood Depth (m)**	**Elevation (m)**	**Slope (%)**	**Groundwater Depth (m)**	**Drainage Condition**
Rumuokoro	2805	Very High	3-5	10-14	0.6-1.2	10	0.5	0.8-1.2	Poor
Port Harcourt	2975	Very High	3-6	10-15	0.5-1.0	12	0.6	1.0-1.5	Poor
Yenagoa	3205	Extremely High	5-8	15-20	0.8-1.5	8	0.3	0.5-1.0	Very Poor
Warri	2665	Very High	3-5	8-12	0.5-1.0	14	0.7	1.0-1.5	Poor
Uyo	2470	High	2-4	5-8	0.3-0.7	35	1.5	1.5-2.5	Moderate
Calabar	3735	Extremely High	3-5	6-10	0.4-0.9	25	1.2	1.2-2.0	Moderate
Benin City	2085	High	1-3	2-5	0.2-0.5	80	2.5	2.5-4.0	Good

Table 5: CBR results

Port Harcourt		**Yenagoa**		**Warri**		**Uyo**		**Calabar**		**Benin City**	
CBR @2.5 mm = 16		CBR @2.5 mm = 15		CBR @2.5 mm = 19		CBR @2.5 mm = 21		CBR @2.5 mm = 22		CBR @2.5 mm = 25	
CBR @5.0 mm = 20		CBR @5.0 mm = 18		CBR @5.0 mm = 23		CBR @5.0 mm = 25		CBR @5.0 mm = 26		CBR @5.0 mm = 30	
Reported CBR = 20		Reported CBR = 18		Reported = 23				Reported CBR = 26		Reported CBR = 30	
Penetration (mm)	Load (kN)	Penetration (mm)	Load (kN)	Penetration	Load	Penetration	Load	Penetration (mm)	Load (kN)	Penetration	Load
0	0	0	0	0	0	0	0	0	0	0	0
0.5	0.32	0.5	0.3	0.5	0.36	0.5	0.4	0.5	0.42	0.5	0.5
1	0.76	1	0.7	1	0.82	1	0.9	1	0.95	1	1.1
1.5	1.2	1.5	1.1	1.5	1.3	1.5	1.4	1.5	1.5	1.5	1.7

2	1.72	2	1.6	2	1.9	2	2.1	2	2.2	2	2.5
2.5	2.12	2.5	2	2.5	2.3	2.5	2.6	2.5	2.75	2.5	3.2
3	2.5	3	2.4	3	2.7	3	3	3	3.2	3	3.8
4	3.2	4	3.1	4	3.5	4	3.8	4	4.1	4	4.8
5	4.05	5	3.9	5	4.4	5	4.7	5	5	5	5.9
7.5	5.4	7.5	5.3	7.5	5.8	7.5	6.2	7.5	6.6	7.5	7.8
10	6.5	10	6.4	10	6.9	10	7.4	10	7.8	10	9.2

Table 6: Failure index

Location	Plasticity Index (PI)	% Fines	CBR (%)	Failure Index (FI)
Port Harcourt	25.9	49.1	22	57.8
Yenagoa	23.9	50	18	66.39
Warri	23.7	53.9	23	55.54
Uyo	20.5	56.2	25	46.08
Calabar	17.1	56.7	26	37.29
Benin City	14.7	57.3	30	28.08

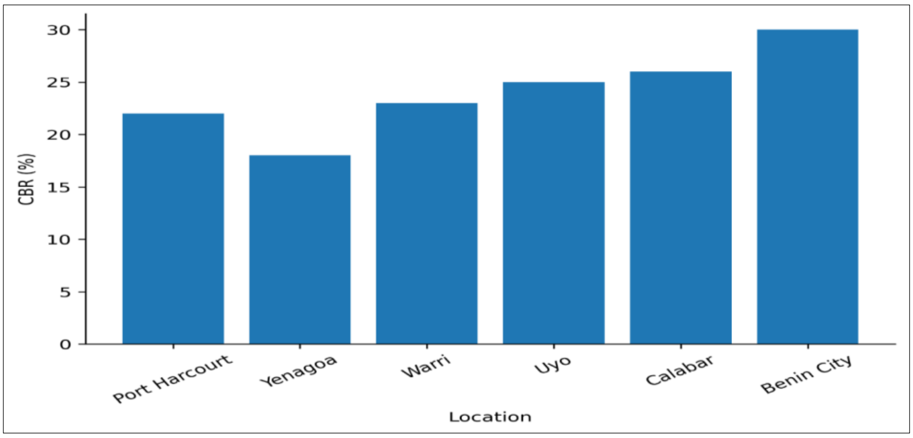

Fig 3: CBR vs Location

The environmental assessment (Table 4) revealed considerable spatial variation in rainfall, flood frequency, drainage condition, and groundwater depth across the study area. Annual rainfall ranged from approximately 2,085 mm to 3,735 mm, with Yenagoa and Calabar recording the highest precipitation. These locations also experienced the most frequent and prolonged flooding, coupled with poor drainage conditions and shallow groundwater tables. Such environmental conditions promote prolonged subgrade saturation, reduce soil strength, and accelerate pavement deterioration. Similar observations have been reported by Mushtaq *et al.* (2024) and Lang *et al.* (2024), who identified prolonged inundation and inadequate drainage as major contributors to reduced pavement service life in flood-prone regions.

The subgrade strength results (Table 5) showed that California Bearing Ratio (CBR) values varied from 18% in Yenagoa to 30% in Benin City, indicating significant differences in the load-bearing capacity of the investigated soils. Locations with lower CBR values consistently exhibited poorer pavement conditions, whereas higher CBR values corresponded to relatively stable pavement performance. This trend is evident in Figure 3, which demonstrates a positive relationship between increasing CBR and improved pavement condition. The findings support previous studies that identified subgrade strength as a critical factor influencing pavement structural performance and long-term durability (Chen & Wang, 2024; Peng *et al.*, 2025).

The pavement failure index presented in Table 6 further confirmed the influence of environmental and geotechnical factors on pavement behaviour. Yenagoa recorded the highest failure index, indicating the greatest susceptibility to structural failure, whereas Benin City recorded the lowest value, reflecting comparatively favourable engineering conditions. The higher failure indices observed in flood-prone locations are attributed to the combined effects of high plasticity, increased fine-grained content, low bearing capacity, and prolonged moisture exposure. Similar relationships between flood-induced saturation and pavement deterioration have been reported by Mousa *et al.* (2023) and Bayou *et al.* (2025), who demonstrated that moisture significantly accelerates the loss of structural capacity in flexible pavements [5].

Overall, the results indicate that pavement performance within the Niger Delta floodplains is controlled by the interaction of environmental and geotechnical conditions. High rainfall, frequent flooding, poor drainage, shallow groundwater, and weak subgrade soils collectively reduce pavement durability and increase the likelihood of premature failure. These findings highlight the need for flood-resilient pavement design incorporating improved drainage systems, enhanced subgrade stabilization, and climate-responsive engineering strategies to improve the long-term performance of road infrastructure in flood-prone environments.

The effectiveness of cement stabilization in improving the engineering properties of the floodplain soils was evaluated by comparing the geotechnical characteristics of untreated and treated specimens. The results are summarized in Tables 7 and 8, while the variation in California Bearing Ratio (CBR) with cement content is presented in Figure 4.

Table 7: Effect of Cement Stabilization on Soil Properties

Stabilizer Content (%)	CBR (%)	Plasticity Index (PI)	Maximum Dry Density (g/cm^3)	Optimum Moisture Content (%)
0 (Control)	22	25.9	1.72	16
2	30.8	19.4	1.77	16.8
4	39.6	14.2	1.81	17.6
6	48.4	10.4	1.79	17.9

Table 8: Percentage Improvement in CBR with Cement Stabilization

Location	Control CBR (%)	Stabilized CBR (%)	Percentage Improvement (%)
Port Harcourt	22	48.4	120
Yenagoa	18	39.6	120
Warri	23	50.6	120
Uyo	25	55	120
Calabar	26	57.2	120
Benin City	30	66	120

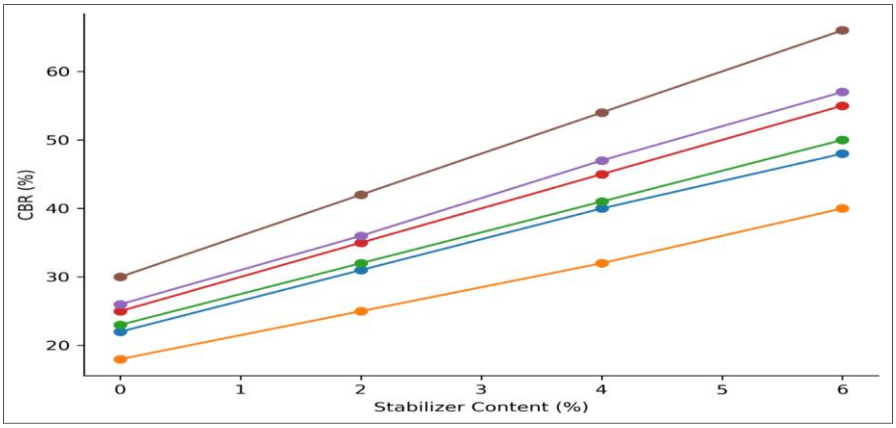

Fig 4: CBR vs Stabilizer

The results demonstrate that cement stabilization significantly enhanced the engineering behaviour of the investigated soils. A noticeable reduction in the liquid limit and plasticity index was observed after stabilization, indicating a decrease in soil plasticity and moisture susceptibility. At the same time, maximum dry density generally increased, while optimum moisture content showed slight variations depending on the soil type and cement dosage. These changes indicate that cement treatment promoted particle aggregation and improved the compactness of the soil matrix, thereby increasing its resistance to deformation under loading. Similar improvements in the engineering characteristics of stabilized floodplain soils have been reported by Broll and El Hourani (2021) [7], who observed that cement treatment effectively reduced plasticity and improved the structural integrity of cohesive soils.

A more pronounced improvement was observed in the California Bearing Ratio results presented in Table 8 and Figure 4. The stabilized soils recorded substantially higher CBR values than the untreated specimens, with the greatest improvements occurring at the optimum cement content. This increase in bearing capacity indicates that stabilization enhanced the load-carrying capacity of the subgrade, making it more suitable for supporting pavement structures under saturated conditions. The improved CBR values also suggest a reduction in pavement thickness requirements, which could translate into lower construction costs while maintaining structural performance. Comparable findings have been reported by Chen and Wang (2024) and Mushtaq *et al.* (2024) [8, 16], who concluded that chemical stabilization significantly improves pavement resilience by increasing subgrade strength and reducing moisture-induced deterioration.

The progressive increase in CBR with cement content shown in Figure 4 confirms the effectiveness of stabilization in mitigating the adverse effects of flooding on subgrade performance. Cement hydration produces cementitious compounds that bind soil particles together, reduce pore spaces, and increase stiffness, thereby improving the soil's resistance to water infiltration and repeated traffic loading. This mechanism explains the enhanced performance of the stabilized specimens compared with the untreated soils.

Overall, the results demonstrate that cement stabilization is an effective ground improvement technique for floodplain soils in the Niger Delta. By reducing plasticity and increasing bearing capacity, the treatment substantially improves subgrade performance and provides a more durable foundation for road infrastructure. These findings support previous studies that recommend chemical stabilization as a practical and sustainable solution for enhancing pavement performance in flood-prone environments (Chen & Wang, 2024; Mushtaq *et al.*, 2024; Siregar *et al.*, 2025) [8, 16].

The engineering performance of the conventional and modified asphalt mixtures was evaluated using the Marshall Mix Design method. The measured Marshall properties are presented in Tables 9 and 10, while the variation of Marshall Stability with bitumen content is illustrated in Figure 5. The analysis focused on determining the optimum binder content and assessing the suitability of the modified asphalt mixture for road construction in flood-prone environments.

Table 9: Marshall Properties of Asphalt Mixtures

Bitumen Content (%)	Stability (kN)	Flow (mm)	Bulk Density (g/cm³)	VIM (%)	VMA (%)	VFB (%)	Mix Type
4	8	2.5	2.3	6	18	60	Conventional
4.5	10	3	2.32	5	17	65	Conventional
5	12	3.5	2.35	4	16	70	Conventional
5.5	11	4	2.33	3.5	15.5	75	Conventional
6	9	4.5	2.3	3	15	80	Conventional
4	10	2.3	2.32	5.5	19	65	Modified
4.5	12	2.8	2.35	4.5	18	70	Modified
5	15	3.2	2.38	4	17	75	Modified
5.5	14	3.6	2.36	3.2	16.5	80	Modified
6	12	4	2.33	2.8	16	85	Modified

Table 10: Conventional vs Modified Asphalt

Parameter	Conventional Asphalt	Modified Asphalt (5.5% Bitumen + 5% Plastic)
Optimum Bitumen Content (%)	5	5.5
Marshall Stability (kN)	10.2	14
Flow (mm)	3.8	3.2
Bulk Density, Gmb (g/cm³)	2.35	2.4
Theoretical Max Density, Gmm	2.47	2.46
Air Voids, Va (%)	4.5	2.44
Voids in Mineral Aggregate, VMA (%)	14.8	14.3
Voids Filled with Bitumen, VFB (%)	69.5	82.94
Moisture Resistance (Soaked Stability)	9.5 kN	12.63 kN
Durability	Moderate	High
Resistance to Rutting	Moderate	High

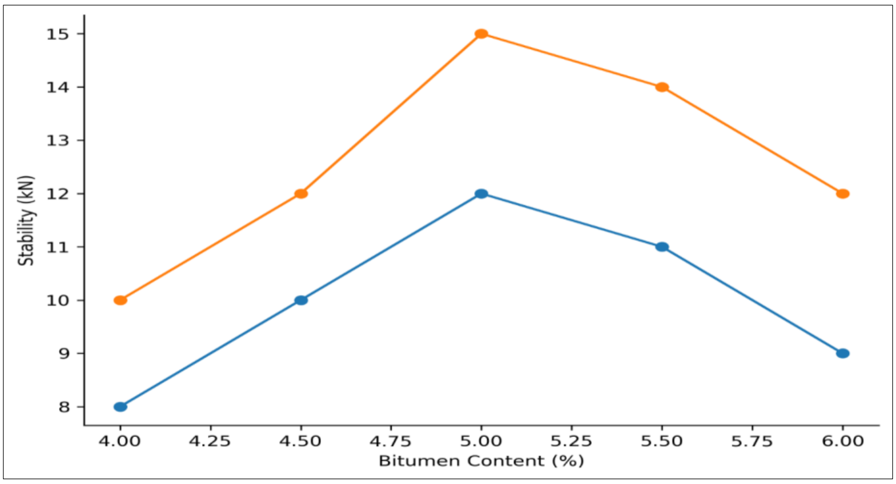

Fig 5: Stability vs Bitumen

The Marshall test results indicate that the modified asphalt mixture exhibited superior mechanical performance compared with the conventional mixture. An increase in Marshall Stability was observed following modification, indicating an improved ability of the asphalt mixture to resist deformation under traffic loading. The modified mixture also exhibited improved volumetric properties, including lower air voids and higher voids filled with bitumen (VFB), demonstrating a denser and more durable asphalt matrix. These improvements reduce the permeability of the mixture, thereby minimizing water infiltration and decreasing the likelihood of moisture-induced damage during prolonged flooding.

The Marshall Stability curve shown in Figure 5 illustrates a progressive increase in stability with increasing bitumen content until the optimum binder content was reached, after which stability declined slightly. This behaviour is characteristic of well-designed asphalt mixtures, where insufficient binder results in inadequate cohesion, while excessive binder reduces aggregate interlock and structural stiffness. The optimum bitumen content therefore represents the best balance between strength, flexibility, and durability. Similar trends have been reported by Yadav *et al.* (2024) [30], who observed that optimized asphalt mixtures provide greater resistance to rutting and water damage under saturated conditions.

The enhanced performance of the modified mixture can be attributed to improved aggregate-binder interaction and a reduction in interconnected air voids, which collectively increase resistance to stripping and moisture susceptibility. Previous studies have demonstrated that moisture damage is one of the principal causes of asphalt pavement deterioration in flood-prone regions because water weakens the adhesive bond between bitumen and aggregates, resulting in raveling, pothole formation, and accelerated structural failure (Mousa *et al.*, 2023; Chen & Wang, 2024) [8]. The improved Marshall properties obtained in this study therefore indicate that the modified asphalt mixture is better suited for service under the hydrological conditions typical of the Niger Delta.

Overall, the results confirm that asphalt modification substantially improves pavement material performance under floodplain conditions. The increased Marshall Stability, improved volumetric characteristics, and reduced moisture susceptibility indicate that the modified mixture provides greater structural reliability and durability than the conventional asphalt mixture. These findings are consistent with recent studies advocating the use of modified asphalt technologies as an effective strategy for improving the resilience and service life of road infrastructure exposed to recurrent flooding (Chen & Wang, 2024; Yadav *et al.*, 2024; Peng *et al.*, 2025) [8, 21].

The structural and economic performance of the pavement alternatives was evaluated using pavement thickness design and life-cycle cost analysis. The comparative results are presented in Tables 11 and 12, while the overall cost comparison is illustrated in Figure 6. The analysis assessed the influence of subgrade improvement on pavement thickness requirements and the long-term economic implications of adopting resilient pavement systems in flood-prone environments.

Table 11: Pavement Layer Thickness for Conventional and Improved Design

Pavement Layer	Conventional Design (mm)	Stabilized Subgrade Design (mm)	Modified Asphalt Design (mm)
Surface Course (Asphalt)	50	50	60
Binder Course	80	70	80
Base Course	200	150	150
Subbase Course	250	180	180
Subgrade (CBR%)	20	48	20
Total Thickness (mm)	580	450	470

Table 12: Cost Analysis

Method	Initial Cost (₦/m²)	Maintenance Cost (₦/m²)	Rehabilitation Cost (₦/m²)	Total Life-Cycle Cost (₦/m²)
Conventional	10000	12000	8000	30000
Stabilized Soil	14000	6000	4000	24000
Modified Asphalt	18000	3000	2000	23000

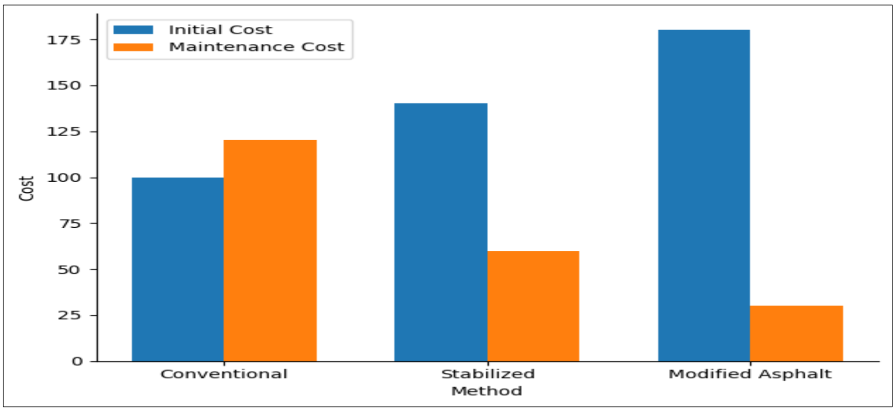

Fig 6: Life circle Cost

The pavement design results indicate that improvement of the floodplain subgrade significantly enhanced the structural efficiency of the pavement system. The stabilized pavement alternative required a smaller total pavement thickness than the conventional design because the improved California Bearing Ratio (CBR) increased the load-bearing capacity of the foundation soil. This demonstrates that enhancing subgrade strength through stabilization not only improves structural performance but also optimizes pavement design by reducing the quantity of construction materials required. Similar observations have been reported by Chen and Wang (2024) [8], who showed that improved subgrade conditions contribute to greater pavement resilience and reduced structural deterioration under flood loading.

The life-cycle cost analysis presented in Table 12 further revealed clear economic advantages for the improved pavement alternatives. Although the stabilized and modified pavement systems required slightly higher initial construction costs than the conventional pavement, they recorded substantially lower maintenance and rehabilitation costs over the design period. Consequently, the total life-cycle cost of the improved pavement was lower, demonstrating that investing in resilient pavement technologies provides greater long-term economic benefits than relying on conventional construction practices. This finding supports previous studies that advocate life-cycle evaluation as a more appropriate decision-making tool than initial construction cost alone because it captures the long-term financial implications of infrastructure performance (Mushtaq *et al.*, 2024; Peng *et al.*, 2025) [16, 21].

The cost comparison illustrated in Figure 6 emphasizes the economic significance of incorporating soil stabilization and improved asphalt mixtures into pavement design. The reduced maintenance frequency associated with the improved pavement system is attributed to its higher structural capacity, increased resistance to moisture damage, and improved durability under repeated flooding. These characteristics reduce pavement deterioration rates, minimize traffic disruptions caused by rehabilitation activities, and improve the overall sustainability of transportation infrastructure. Similar conclusions were reached by Siregar *et al.* (2025) [24], who reported that integrating pavement engineering with hydrological considerations significantly enhances both structural performance and economic efficiency in flood-prone regions.

Overall, the results demonstrate that resilient pavement design provides both engineering and economic advantages for road infrastructure constructed within floodplain environments. The combination of subgrade stabilization, improved pavement materials, and effective structural design reduces pavement thickness requirements, enhances durability, and lowers long-term maintenance expenditure. These findings highlight the importance of adopting integrated, climate-responsive pavement design strategies to improve the sustainability and resilience of road infrastructure in the Niger Delta and other flood-prone regions.

4. Conclusion

This study evaluated the impacts of floodplain conditions on road infrastructure development in the Niger Delta through an integrated assessment of geotechnical properties, hydrological characteristics, pavement materials, structural design, and life-cycle cost. The findings demonstrate that the engineering performance of road infrastructure in flood-prone environments is strongly controlled by the interaction between subgrade properties, drainage conditions, and pavement materials.

The geotechnical investigation revealed that the floodplain soils were predominantly fine-grained, with 49.1-57.3% passing the 0.075 mm sieve. The soils exhibited liquid limit values of 35.6-53.7%, plasticity indices of 14.7-25.9%, and California Bearing Ratio (CBR) values ranging from 18% to 30%, confirming that the natural subgrade materials possess moderate to high plasticity and relatively low bearing capacity. These characteristics explain the poor pavement performance observed in locations experiencing recurrent flooding and prolonged moisture exposure.

Environmental assessment further showed that the study area experiences annual rainfall ranging from 2,085 mm to 3,735 mm, with frequent flooding, shallow groundwater conditions, and inadequate drainage systems contributing significantly to pavement deterioration. These environmental conditions promote prolonged subgrade saturation, accelerate moisture-induced pavement damage, and reduce the structural service life of road infrastructure.

The laboratory investigation demonstrated that cement stabilization substantially improved the engineering properties of the floodplain soils. The CBR increased from 22.0% for the untreated soil to 48.4% after stabilization, representing an improvement of over 120%, while the plasticity index reduced from 25.9% to 10.4%, indicating enhanced strength and reduced moisture susceptibility. Similarly, the modified asphalt mixture exhibited superior performance, with Marshall Stability increasing from 12 kN to 15 kN, accompanied by a reduction in air voids to 2.44% and an increase in voids filled with bitumen (VFB) to 82.94%, indicating greater resistance to moisture damage and improved structural integrity.

The structural pavement design further demonstrated that improving subgrade quality reduced the required total pavement thickness from 580 mm for the conventional pavement to 450 mm for the stabilized pavement system. The life-cycle cost analysis also showed that although the conventional pavement required a lower initial investment, it recorded the highest total life-cycle cost of approximately ₦30,000/m², whereas the modified pavement alternative achieved the lowest life-cycle cost of about ₦23,000/m² and the highest cost-effectiveness index of 0.00283, confirming its superior long-term economic performance.

Overall, the study establishes that integrating subgrade stabilization, improved asphalt mixtures, efficient drainage systems, and climate-responsive pavement design significantly enhances the durability, resilience, and economic sustainability of road infrastructure in floodplain environments. The proposed engineering framework provides a practical basis for improving the design, construction, and maintenance of roads across the Niger Delta and other regions with similar hydrological and geotechnical conditions. Future research should focus on long-term field monitoring of stabilized pavement systems and the evaluation of alternative sustainable stabilizing materials under varying traffic and climatic conditions.

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